# Assessment of Water and Fertilizer Management Impacts on CH4 Emissions from Paddy Fields and Their Global Warming Potential: Postprint

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## Abstract

Methane (CH4) is one of the major greenhouse gases, second only to carbon dioxide (CO2) in its contribution to global warming. Rice paddies are an important source of CH4 emissions, and reducing CH4 emissions from rice paddies has a direct effect on mitigating climate warming. Therefore, understanding the patterns and characteristics of CH4 emissions from rice paddies is particularly important for controlling and reducing such emissions. To understand the main influencing factors and their effects on greenhouse gas emissions from rice paddies, estimate the global warming potential of greenhouse gases from rice paddies, and seek mitigation measures for agricultural fields, we established a database of CH4 emissions from rice paddies by collecting published literature and employed factorial analysis and regression analysis methods to analyze the characteristics of daily CH4 emissions and global warming potential as well as possible influencing factors. The results showed that both daily CH4 emissions and warming potential from rice paddies increased with the background content of soil organic matter. The magnitude of daily CH4 emissions from different types of rice paddies followed the order: late rice in double-cropping system > early rice in double-cropping system > single-crop rice > late rice in rice-wheat rotation system; the warming potential of CH4 from late rice paddies was greater than that from early rice paddies. Under different fertilizer treatment conditions, daily CH4 emissions from rice paddies exhibited the following pattern: straw incorporation > combined application of organic fertilizer > chemical nitrogen fertilizer  biochar. Controlling irrigation water amount could reduce the comprehensive global warming potential of CH4 from rice paddies, showing the pattern: continuous flooding > midseason drainage > alternate wetting and drying > controlled irrigation. The research results indicate that the production and emission processes of CH4 from rice paddies are jointly influenced by multiple factors including soil organic matter content,

fertilizer management, water management, and cropping system. Fertilizer and water management should be appropriately adjusted according to different soil conditions and planting systems to reduce greenhouse gas emissions from rice paddies and decrease their warming potential.

## Full Text

# Impact of Water/Fertilizer Management on Methane Emission in Paddy Fields and on Global Warming Potential

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### Abstract

Methane (CH ) is a key greenhouse gas, second only to CO in terms of contribution to global warming. Paddy fields represent an important source of CH emissions, and reducing these emissions has direct implications for mitigating climate change. Understanding the patterns and characteristics of CH emissions from rice paddies is therefore crucial for developing effective control strategies. To identify the main factors influencing greenhouse gas emissions from paddy fields, estimate their global warming potential, and explore mitigation options, we constructed a comprehensive database of CH emissions from rice paddies by compiling published literature. Factorial and regression analyses were employed to examine the characteristics of daily CH emissions and global warming potential, along with their potential influencing factors. The results demonstrated that both daily CH emissions and warming potential increased with rising soil organic matter background content. Among different paddy types, daily CH emissions followed the order: late rice of double-cropping system > early rice of double-cropping system > single-cropping rice > late rice of rice-wheat rotation. The global warming potential of CH was greater in late rice paddies than in early rice paddies. Under different fertilizer treatments, daily CH emissions exhibited the following pattern: straw turnover > combined organic manure > chemical nitrogen fertilizer  biochar. Controlled irrigation significantly reduced the comprehensive global warming potential of CH , with the ranking: continuous flooding > field drying > flooding-drying alternation > control irrigation.

These findings indicate that CH production and emission processes in paddy fields are jointly influenced by multiple factors, including soil organic matter content, fertilizer and water management, and cropping systems. Management practices should be tailored to specific soil conditions and cropping systems to effectively reduce greenhouse gas emissions and minimize warming potential.

**Keywords:** Paddy field; Greenhouse gases; Methane emission; Global warming potential; Soil organic matter; Water and fertilizer management; Cropping system

## Introduction

Methane (CH ) is one of the three major greenhouse gases, ranking second only to carbon dioxide (CO ) in its contribution to global warming. Rice paddies constitute a significant source of CH emissions, accounting for approximately 15% of total atmospheric CH emissions [1]. According to China’ s Second National Communication on Climate Change [2], agricultural CH emissions in 2005 represented 56.6% of the nation’ s total CH emissions, with paddy fields contributing 31.5% of agricultural CH emissions. China’ s rice cultivation area comprises about 25% of the country’ s total arable land and approximately 20% of global rice cultivation area. Consequently, reducing CH emissions from rice paddies is critically important for climate change mitigation.

Methane emissions from rice paddies result from the decomposition of organic matter under strictly anaerobic conditions, representing a highly complex process [3] influenced by soil physicochemical properties, climatic conditions, tillage systems, rice varieties, and field management practices [4]. CH production occurs through two primary pathways: an acidogenic pathway and a non-acidogenic pathway. The former involves specialized hydrogenotrophic methanogens that reduce CO using H or directly utilize formic acid and CO to form CH . The latter involves methylotrophic methanogens that demethylate simple methyl-containing compounds, accounting for approximately 70% of CH production and representing the dominant pathway. Once produced, CH is transported to the atmosphere through three routes: molecular diffusion, ebullition, and plant-mediated transport via aerenchyma tissue [5], with the latter being the primary emission pathway [6]. Rice roots exhibit strong CH transport capacity, with approximately 80% of CH emissions occurring through the plant’ s aerenchyma system [7-8].

Key factors influencing CH emissions from paddy fields include soil temperature, pH, water management, and fertilizer application. Soil temperature directly affects organic matter decomposition, microbial activity, and the rate of CH production and transport to the atmosphere. The optimal temperature for methanogenic microbial activity is 35–37 °C, and during the rice growing season, daily variations in CH flux correspond closely with diurnal changes in soil temperature [9]. Soil pH primarily influences the decomposition rate of organic matter and methanogen activity, with neutral conditions favoring CH production. When pH falls below 5.75 or exceeds 8.75, methanogenic activity is suppressed, substantially reducing or eliminating CH emissions [10]. In flooded rice paddies with high soil organic matter content, methanogen activity is elevated, resulting in greater CH emissions that show significant positive correlation with soil organic matter content [11-12]. Irrigation methods and water depth also affect CH emissions, with shallow irrigation reducing emissions. When irrigation depth is within 10 cm, CH flux increases with water depth [13]. Compared with continuous flooding, mid-season drainage can reduce CH emissions by 36–65% [14-16], while intermittent irrigation can decrease emissions by 32–93% [17-19].

Different water management practices create a clear trade-off relationship between CH and N O emissions from rice paddies [20]. While reducing CH emissions often leads to increased N O emissions [8], the global warming potential of N O is substantially higher than that of CH [9]. Therefore, when modifying water management practices to mitigate CH emissions, it is essential to consider N O emissions and their combined effects. Nitrogen fertilizer indirectly influences CH emissions by affecting other factors. Increased nitrogen application can suppress CH emissions from rice paddies [21], with the most significant reduction occurring when nitrogen application rates increase from low to moderate levels, while changes from moderate to high rates show minimal additional effect [22]. Urea application results in higher CH emissions compared to ammonium nitrate and ammonium sulfate [23]. Straw and green manure incorporation significantly increases CH emissions, with emissions rising as incorporation rates increase [24]. Additionally, applying unfermented farmyard manure and manure residues increases CH emissions, whereas fermented biogas residues can reduce emissions [21]. Combined application of chemical and organic fertilizers effectively reduces CH emissions without affecting yield, representing one of the most effective mitigation strategies.

Numerous studies have measured and monitored CH emissions from Chinese rice paddies, revealing distinct regional patterns. The highest emission fluxes occur in southwestern China, averaging 16.8 mg(CH) · m$^{2}$ · h$^{1}$, followed by the middle and lower reaches of the Yangtze River region, with relatively lower emissions in northern and southern China, and the lowest fluxes in northeast China [25]. Peak CH emissions during the entire rice growth period occur at the regreening and tillering stages. To facilitate estimation of greenhouse gas emissions from rice paddies, this study compiled published literature to establish a comprehensive database [25]. We conducted factorial analyses of CH emissions under different management practices for various rice cultivation systems (early rice of double-cropping, late rice of double-cropping, typical single-cropping rice, and rice-wheat rotation) to identify the main influencing factors and their relative importance, and to analyze the comprehensive global warming potential of greenhouse gas emissions under different water management practices, providing a scientific basis for estimating CH emissions and developing reasonable mitigation strategies.

### 1.1 Data Sources

We systematically searched literature databases (CNKI, Wanfang, VIP, ScienceDirect, and SpringLink) for domestic and international journal articles and graduate theses published before 2015 related to CH emissions from Chinese rice paddies. Search keywords included "CH emission," "methane," "water management," and "fertilizer management."

### 1.2 Database Construction

Data were entered and hierarchically categorized using Excel spreadsheets. The raw database included: literature information (author, year, source), experimental site details (location, soil type, texture, pH, soil organic matter, total nitrogen, clay content, crop type, growth period duration), water and fertilizer management (irrigation status, irrigation method, drainage practice, fertilization method, application rate, nitrogen fertilizer type and amount), daily CH emission rates, and global warming potential values. Nitrogen application rates were standardized to kg(N) · hm$^{2}$. Daily CH emission rates were expressed as kg(CH ) · hm$^{2}$ · d$^{1}$, and global warming potential (GWP) as kg(CO -e) · hm$^{2}$ · d$^{1}$.

Global warming potential represents the relative radiative forcing of a given substance compared to CO over a specific time horizon, serving as a parameter to evaluate the relative climate change impact of various greenhouse gases. According to IPCC greenhouse gas inventory methodology [26], the GWP of CH over a 100-year time horizon is calculated as:

$$\text{GWP} = \text{cumulative emissions} \times 25$$

### 1.3 Data Analysis

To ensure data representativeness, literature included in the database had to meet the following criteria: (1) data originated from field experiments; (2) basic information including experimental time, location, soil physicochemical properties, experimental design, and field management was clearly reported; (3) CH and N O sampling methods were scientifically sound, with observations covering at least one complete crop growth period. Database data were stratified into subgroups (Table 1 ). Due to variations in growth period length, soil properties, and temperature during the growing season among different rice cultivation systems, CH emissions and warming potential differed accordingly. Since CH emissions from rice paddies primarily result from organic matter decomposition under flooded conditions, we stratified data by soil organic matter content for factorial analysis ( 25 g · kg$^{1}$ and >25 g · kg$^{1}$ for fertilizer treatments; 30 g · kg$^{1}$ and >30 g · kg$^{1}$ for water management treatments). Paddies were further categorized as early rice, late rice, and single-cropping rice, with CH and N O emissions analyzed in subgroups based on fertilizer type, soil amendments, and water management. Factorial analyses were conducted according to CH emission patterns under fertilizer and water treatments, with GWP values summarized to analyze potential influencing factors.

Chemical fertilizers included urea and compound fertilizers, while organic fertilizers primarily consisted of animal manure mixed with soil or straw. Straw turnover referred to complete or partial return of previous season wheat and rice straw. Biochar was produced from crop residues through high-temperature carbonization under anaerobic conditions. Continuous flooding (CF) maintained flooded conditions throughout the growing season until drainage one week before harvest. Field drying (FDF) involved flooding after transplanting, drainage and drying at the end of tillering stage, reflooding, and final drainage 1-2 weeks before harvest. Flooding-drying alternation (FD) followed the same pattern as FDF but implemented alternating wet-dry cycles after reflooding until final drainage. Control irrigation (CI) maintained continuous alternating wet-dry conditions or kept the field moist without standing water throughout the entire growth period.

For outlier data, we first applied empirical removal based on published literature and theoretical analysis by establishing upper and lower limits, eliminating data points exceeding these bounds by 100%. Second, we used SPSS statistical software to establish 95% confidence intervals, removing outliers beyond the box plot limits. Median values better represent central tendency, so we selected median values for each data group. The final database comprised 336 data points from 66 sites nationwide. Data analysis and graphing were performed using Excel software.

### 2.1.1 Effects on CH Emissions from Early Rice Paddies

Early rice in China is primarily cultivated in Jiangsu, Zhejiang, Anhui, Hunan, Hubei, and Guangdong/Guangxi regions. Early rice is typically nursed in late March to early April, transplanted in late April to early May, and harvested in mid-to-late July, with a growth period of 85-100 days. The collected CH emission data for early rice paddies mainly came from early rice in double-cropping systems, with nitrogen application rates of 100-300 kg(N) · hm $^{2}$.

CH emissions from rice paddies are influenced not only by background soil organic matter (SOM) content but also by fertilizer type (Figure 1 [Figure 1: see original paper]). When SOM  25 g · kg $^{1}$, early rice paddies receiving only chemical nitrogen fertilizer had a median daily CH emission of 1.61 kg(CH ) · hm $^{2}$ · d $^{1}$, while those receiving combined organic manure showed 1.83 kg(CH ) · hm $^{2}$ · d $^{1}$. Chemical fertilizer combined with straw turnover significantly increased emissions to a median of 2.49 kg(CH ) · hm $^{2}$ · d $^{1}$. As SOM content increased, CH emissions showed an upward trend: when SOM > 25 g · kg $^{1}$, daily CH emissions from combined organic manure and straw turnover treatments increased by 0.45 kg(CH ) · hm $^{2}$ · d $^{1}$ and 0.96 kg(CH ) · hm $^{2}$ · d $^{1}$, respectively, representing increases of 24% and 39% compared to SOM  25 g · kg $^{1}$ conditions. In contrast, chemical nitrogen application showed no significant effect on early rice CH emissions across different SOM backgrounds. Limited data on biochar application (all with SOM background > 25 g $\cdot$ kg $^{1}$, n = 8) revealed that biochar amendment reduced daily CH emissions to a median of 1.02 kg(CH ) $\cdot$ hm $^{2}$ $\cdot$ d $^{1}$, significantly lower than other fertilization methods.

### 2.1.2 Effects on CH Emissions from Late Rice Paddies

Late rice includes late rice from double-cropping systems and late rice from rice-wheat rotations, typically nursed in mid-to-late June, transplanted in mid-to-late July, and harvested in late October to early November, with a growth period of 105–130 days. Late rice management receives greater attention due to its greater contribution to total rice yield.

Late rice cultivation regions largely overlap with early rice regions. Overall, CH emissions from late rice paddies were higher than those from early rice (Figure 2 [Figure 2: see original paper] and Table 2 ). Under chemical fertilizer, combined organic manure, and straw turnover treatments, daily CH emissions from double-cropping late rice showed an increasing trend. With background SOM 25 g $\cdot$ kg $^{1}$, median daily emissions were 2.44 kg(CH ) $\cdot$ hm $^{2}$ $\cdot$ d $^{1}$, 2.98 kg(CH ) $\cdot$ hm $^{2}$ $\cdot$ d $^{1}$, and 3.80 kg(CH ) $\cdot$ hm $^{2}$ $\cdot$ d $^{1}$, respectively. Compared to chemical fertilizer alone, combined organic manure and straw turnover increased emissions by 22% and 56%, respectively. With SOM > 25 g $\cdot$ kg $^{1}$, CH emissions under various fertilizer treatments were slightly lower, but biochar application significantly reduced emissions to a median of 1.02 kg(CH ) $\cdot$ hm $^{2}$ $\cdot$ d $^{1}$.

Rice-wheat rotation is a typical cropping system in the middle and lower reaches of the Yangtze River. The rotation disrupts continuous flooding conditions, improving problematic soil characteristics of chronically flooded paddies. Additionally, drainage for winter wheat cultivation suppresses methanogenic activity, effectively reducing CH production and emissions. As shown in Figure 2b, median daily CH emissions from rice-wheat rotation paddies were generally below 2 kg(CH ) $\cdot$ hm $^{2}$ $\cdot$ d $^{1}$. With SOM 25 g $\cdot$ kg $^{1}$, median emissions were 0.55 kg(CH ) $\cdot$ hm $^{2}$ $\cdot$ d $^{1}$ and 0.51 kg(CH ) $\cdot$ hm $^{2}$ $\cdot$ d $^{1}$ under chemical fertilizer and biochar amendment, respectively, and 0.99 kg(CH ) $\cdot$ hm $^{2}$ $\cdot$ d $^{1}$ and 1.82 kg(CH ) $\cdot$ hm $^{2}$ $\cdot$ d $^{1}$ under combined organic manure and straw turnover. With SOM > 25 g $\cdot$ kg $^{1}$, median daily CH emissions under all fertilizer treatments increased compared to low SOM conditions, with substantial differences observed under chemical fertilizer alone. The ranking of CH emissions was: straw turnover > combined organic manure > chemical nitrogen > biochar amendment, with biochar significantly reducing emissions.

### 2.1.3 Effects on CH Emissions from Single-Cropping Rice Paddies

Single-cropping rice is primarily distributed in northeast, north, and parts of northwest China, typically nursed around the Qingming Festival (early April), transplanted in late April to early May, and harvested in late September to early October, with a growth period of 120–150 days. Fertilizer type significantly affected CH emissions (Figure 3 [Figure 3: see original paper]). With SOM 25 g · kg$^{1}$, chemical fertilizer alone resulted in median daily emissions of 0.78 kg(CH ) · hm$^{2}$ · d$^{1}$, while combined organic manure and straw turnover significantly increased emissions by 97% and 283%, respectively. Biochar amendment reduced emissions by 46%. With SOM > 25 g · kg$^{1}$, median daily emissions were 1.08 kg(CH ) · hm$^{2}$ · d$^{1}$ (chemical fertilizer), 2.70 kg(CH ) · hm$^{2}$ · d$^{1}$ (combined organic manure), 6.19 kg(CH ) · hm$^{2}$ · d$^{1}$ (straw turnover), and 0.93 kg(CH ) · hm$^{2}$ · d$^{1}$ (biochar), showing even more pronounced differences.

Daily CH emissions varied considerably across paddy types under different fertilizer and amendment treatments (Table 2). Early rice paddies in double-cropping systems emitted 1.02–3.45 kg(CH ) · hm$^{2}$ · d$^{1}$, while late rice paddies from double-cropping and rice-wheat rotation systems emitted 0.52–3.80 kg(CH ) · hm$^{2}$ · d$^{1}$ and 0.48–1.86 kg(CH ) · hm$^{2}$ · d$^{1}$, respectively. Single-cropping rice paddies emitted 0.78–6.19 kg(CH ) · hm$^{2}$ · d$^{1}$. The ranking of CH emissions was: late rice of double-cropping > early rice of double-cropping > single-cropping rice > late rice of rice-wheat rotation, demonstrating that rice-wheat rotation significantly reduces CH emissions.

### 2.2.1 Effects on Global Warming Potential of CH from Early Rice Paddies

CH production and emission are closely related to soil moisture conditions. During drainage and drying periods, the shift from anaerobic to aerobic conditions significantly promotes nitrification.

Based on water management practices, collected data were divided into four subgroups: continuous flooding (CF), flooding-drying-reflooding-drainage (abbreviated as field drying, FDF), flooding-drying alternation (FD), and control irrigation (CI). As shown in Figure 4 [Figure 4: see original paper] and Table 3 , CH emissions followed the pattern CF > FDF > FD > CI regardless of whether SOM 30 g · kg$^{1}$ or SOM > 30 g · kg$^{1}$. Soil organic matter background clearly affected emissions. When SOM content was low, warming potential was also low; with SOM 30 g · kg$^{1}$, CH warming potential under each irrigation mode decreased by 25%, 12%, 45%, and 39%, respectively, with FD and CI showing significant emission reductions. Continuous flooding produced the highest CH emissions, while mid-season drainage or intermittent irrigation significantly reduced emissions. Overall, the total global warming potential of greenhouse gases from early rice paddies decreased regularly in the order CF, FDF, FD, and CI (Table 3). Thus, control irrigation represents the most effective measure for greenhouse gas mitigation in rice paddies.

### 2.2.2 Comprehensive Effects on CH Emissions from Late Rice Paddies

Compared with early rice paddies, late rice paddies in double-cropping systems showed higher warming potential under all irrigation modes, primarily due to higher air and soil temperatures during the late rice growing season, which intensified carbon and nitrogen transformation processes.

As shown in Figure 5 [Figure 5: see original paper] and Table 3 , CH warming potential in double-cropping late rice paddies varied with water management. With SOM 30 g · kg $^{1}$, CF showed the highest warming potential with a median of 6,700.00 kg(CO -e) · hm $^{2}$, while FDF, FD, and CI reduced emissions by 11%, 49%, and 68% compared to CF. With SOM > 30 g · kg $^{1}$, median CH warming potential under CF was 7,362.67 kg(C) · hm $^{2}$, with FDF, FD, and CI showing reductions of 26%, 60%, and 56%, respectively. Although CI showed slightly higher emissions than FD, the difference was not significant, suggesting minimal influence of soil organic matter on late rice CH emissions.

In rice-wheat rotation late rice paddies (Figure 6 [Figure 6: see original paper] and Table 3 ), global warming potential was generally low when SOM 30 g · kg $^{1}$, decreasing in the order CF, FDF, FD, and CI. However, N O warming potential increased sequentially under different water management modes, accounting for 1%, 3%, 13%, and 50% of total warming potential, respectively. Control irrigation reduced CH emissions but significantly increased N O emissions because the moist, non-flooded or alternating wet-dry conditions disrupted the anaerobic environment suitable for methanogens while creating favorable conditions for nitrification and N O production. Nevertheless, the reduction in CH emissions far exceeded the increase in N O emissions, making water control an effective mitigation measure.

With SOM > 30 g · kg $^{1}$, CH warming potential increased significantly, likely because wheat straw incorporation from the previous season added exogenous organic material that served as the primary substrate for CH production. Under anaerobic conditions, this substrate was rapidly utilized by methanogens and other microorganisms, leading to substantially increased CH production and emissions. Under these conditions, N O warming potential accounted for 7%, 25%, and 81% of total warming potential across different water management modes, while CH contribution rates were 95%, 94%, 91%, and 42%, respectively, confirming CH as the dominant greenhouse gas from rice paddies. The trend remained consistent with SOM 30 g · kg $^{1}$ conditions, with CH warming potential increasing by 47%, 55%, 29%, and 95% under different irrigation modes. Control irrigation reduced global warming potential more than other irrigation modes, demonstrating clear mitigation benefits (Figure 7 [Figure 7: see original paper]).

For all treatments (CF, FDF, FD, CI), the proportion of N O emissions increased sequentially while CH emissions decreased, accounting for 5%, 6%, 9%, and 58% (SOM 30 g · kg $^{1}$) and 2%, 2%, 10%, and 29% (SOM > 30 g · kg $^{1}$) of total warming potential. However, control irrigation still maintained the lowest total global warming potential.

Overall, the global warming potential of greenhouse gases from single-cropping rice paddies decreased in the order CF, FDF, FD, and CI (Table 3). Controlled water management is an effective mitigation measure, reducing greenhouse gas emissions from single-cropping rice paddies by 3–64% compared with continuous flooding, with control irrigation showing the best mitigation effect.

## Discussion

### 3.1 Analysis and Comparison of CH Emissions from Different Paddy Types

Under chemical fertilizer, combined organic manure, and straw turnover treatments, daily CH emissions from late rice paddies were on average 0.5 times higher than those from early rice paddies, likely due to higher temperatures during the late rice growing season that enhanced microbial activity and accelerated decomposition of organic matter and soil organic carbon, resulting in greater daily CH emissions. In contrast, CH emissions from rice-wheat rotation paddies were lower than those from both early and late rice paddies of double-cropping systems, with reductions of 51%, 47%, and 36% compared to early rice, and 66%, 66%, and 59% compared to late rice under chemical fertilizer, combined organic manure, and straw turnover treatments, respectively. It should be noted that the sample size for single-cropping rice was relatively small, and the precision of emission values requires further verification.

Soil organic matter content also affected CH emissions. While late rice paddies showed no significant change in CH emissions with increasing SOM, early rice paddies, rice-wheat rotation paddies, and single-cropping rice paddies all exhibited significant increases [27-28]. When background SOM was high (>25 g · kg$^{1}$), daily CH emissions under chemical fertilizer, combined organic manure, and straw turnover treatments all increased compared to low SOM conditions ( 25 g · kg$^{1}$), with particularly significant increases observed in single-cropping rice paddies.

### 3.2 Effects of Fertilizer Management on CH Emissions

Fertilizer application, particularly organic fertilizers, represents an important factor influencing CH emissions from rice paddies. Different fertilizer types affect CH emissions differently across paddy types. This study demonstrated that combined organic manure and straw turnover both increased daily CH emissions to varying degrees, with the ranking: straw turnover [1.83–3.45 kg(CH ) · hm$^{2}$ · d$^{1}$] > combined organic manure [0.99–2.98 kg(CH ) · hm$^{2}$ · d$^{1}$] > chemical nitrogen fertilizer [0.55–2.44 kg(CH ) · hm$^{2}$ · d$^{1}$]. Following straw turnover, carbon from straw (primarily crude fiber, cellulose, hemicellulose, and lignin) provides organic material to the soil, supplying the substrate for CH production and promoting CH generation and emission [27-28]. Organic manure also contains considerable amounts of readily utilizable carbon (such as organic acids and amino sugars) and humic acids that activate soil microorganisms and stimulate methanogen activity, thereby promoting CH emission [29-30]. The organic fertilizers in this study were primarily farmyard manures (pig and cattle manure) containing highly active, readily decomposable components that enhanced soil organic carbon mineralization and increased the proportion converted to CH under anaerobic conditions.

Compared with combined organic manure and straw turnover, biochar amendment significantly reduced daily CH emissions. However, compared with chemical nitrogen fertilizer alone, the mitigation effect was only evident in double-cropping rice paddies, not in single-cropping rice paddies. This may be because double-cropping paddies remain flooded longer, maintaining lower soil redox potential (Eh) for extended periods. Biochar contains functional groups (-OH, -CH -, C=C, ester C=O) and ash components (K, Na, Ca, Mg) that may improve strongly reduced soil conditions and potentially inhibit CH production [31-32]. Single-cropping rice paddies have shorter flooding periods and relatively weaker reducing conditions, resulting in smaller biochar amendment effects and weaker inhibition of CH production. Due to limited literature on biochar effects on CH emissions from rice paddies, further verification is needed.

### 3.3 Effects of Water Management on Global Warming Potential of CH

Water management controls both aerobic and anaerobic soil conditions and directly affects soil carbon and nitrogen cycling, creating trade-offs between CH and N O emissions and influencing overall global warming potential. Analysis revealed that CH warming potential under different water management practices followed the pattern CF > FDF > FD > CI, though CI showed slightly higher median warming potential than FD in late rice paddies, the overall trend remained decreasing. Total global warming potential from rice paddies consistently ranked as CF > FDF > FD > CI. Methane contributed over 90% on average (ranging from 50% to 99%) to the greenhouse effect, confirming its dominance as the primary greenhouse gas from rice paddies.

Field drying (FDF) is typically implemented for 1-2 weeks during the late tillering stage in well-drained areas. During this period, the shift from anaerobic to aerobic conditions initiates nitrification, releasing N O from nitrogen fertilizer not immediately absorbed by crops. Although N O has a higher global warming potential than CH , the limited duration of drainage results in relatively small N O warming potential (2-58% of total seasonal warming potential) [16-17,27]. Therefore, mid-season drainage under appropriate conditions remains one of the primary mitigation measures for greenhouse gas emissions from rice paddies.

In terms of current drainage conditions in China' s major rice-producing regions, control irrigation requires substantial labor and resources and has not been widely adopted. The most common water management practices remain FDF or FD, making mid-season drainage a relatively simple and feasible mitigation measure.

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